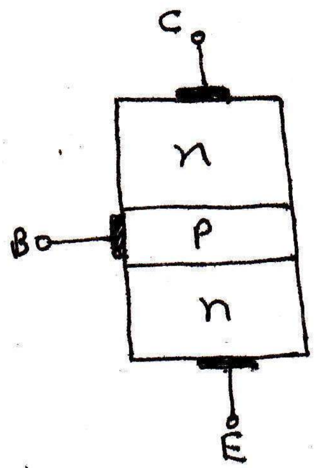
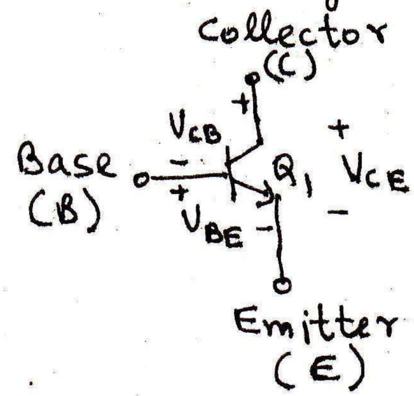
PHYSICS OF BIPOLAR TRANSISTORS

* A bipolar transistor consists of three doped regions forming a sandwich:-
  1. Emitter → emits charge carriers
  2. Base → controls the number of charge carriers making the journey.
  3. Collector → collects the charge carriers.



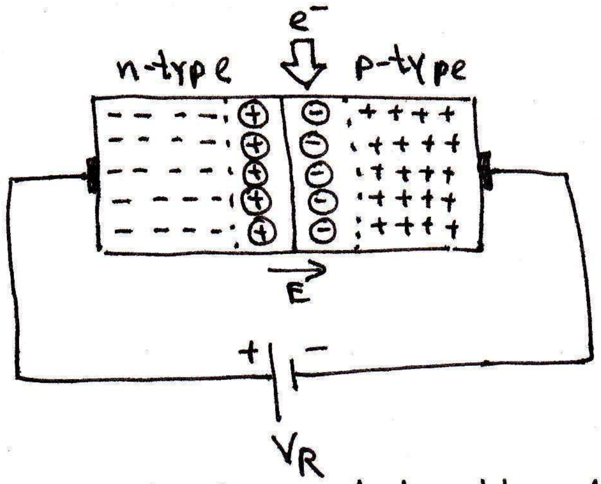
structure



symbol

* Two pn-junctions
  → between base-emitter
  → between base-collector.
* The device is not symmetric with respect to emitter and collector.
* The dimensions and doping levels of emitter and collector are quite different.
* EMITTER AND COLLECTOR CANNOT BE INTERCHANGED.
* Proper operation of the device require that base be a thin region, eg. about 100 Å in modern integrated circuits.

Injection of electrons into depletion region :-



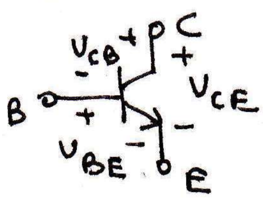
Lets inject an electron into the depletion region in a reverse biased pn-junction.

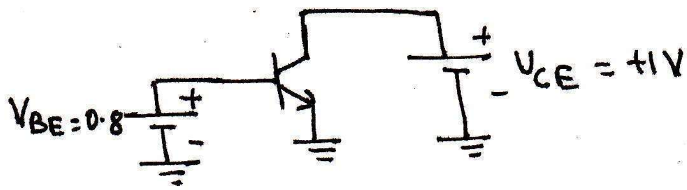
It serves as minority carrier in p-type and is rapidly swept away into n-side by the electric field.

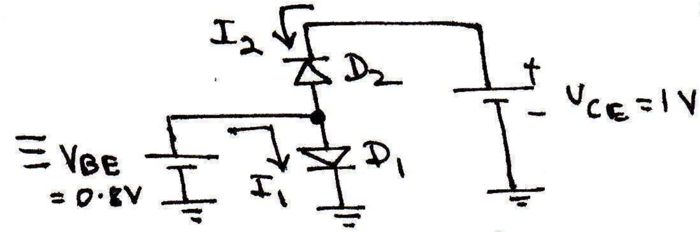
* Ability of the reverse-biased pn-junction to efficiently "collect" externally-injected electrons /holes proves essential to the operation of bipolar transistors.

OPERATION OF BIPOLAR TRANSISTOR IN ACTIVE MODE :-

* In this mode the transistor acts a current source between collector and emitter.
* The above current is controlled by the voltage between base and emitter.
* For a bipolar transistor the terminal voltages V_{BE}, V_{BC}, and V_{CE}, which can assume positive and negative values, there are 2^3 possible cases.
* One ~~is~~ of these combinations is useful.







Simplistic Model

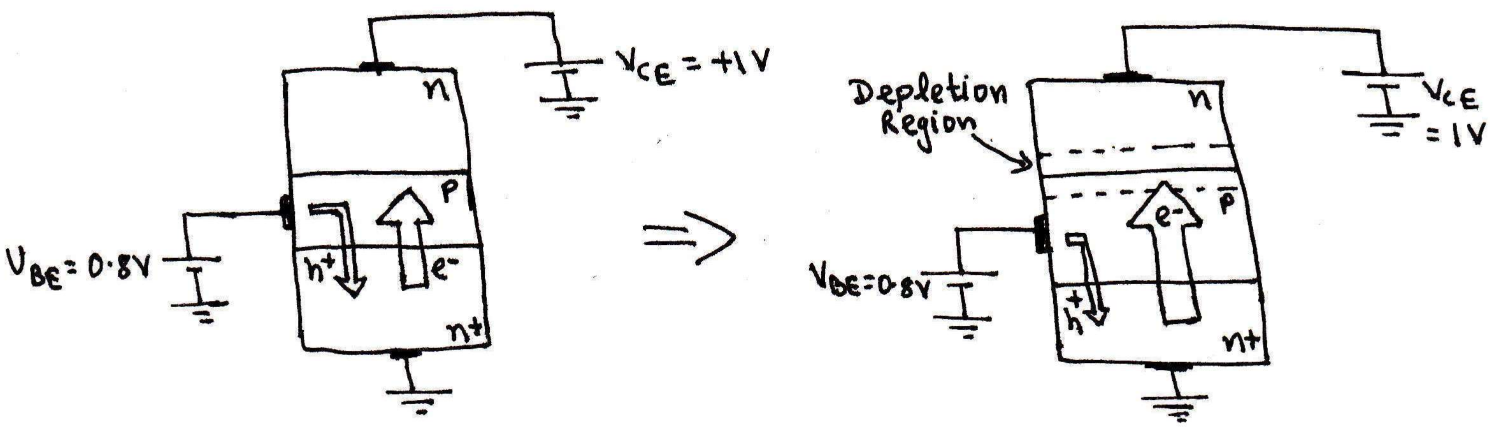
Circuit Condition:- $V_{BE} > 0$

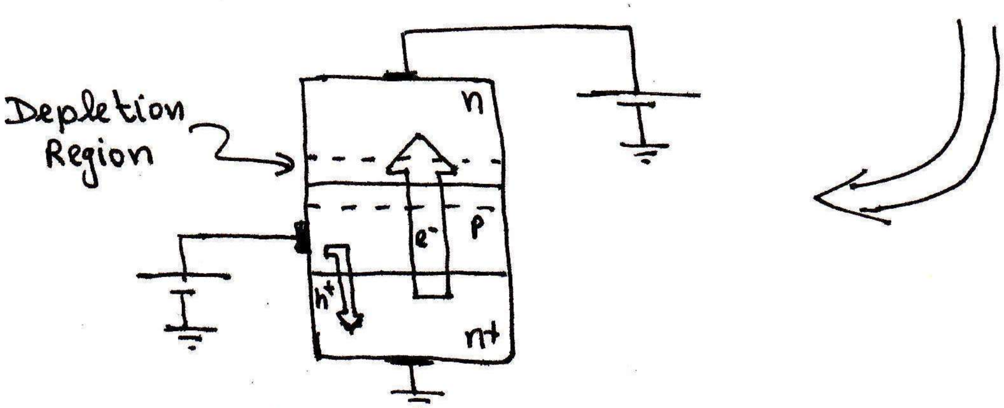
$V_{CE} > 0$

and $V_{BC} < 0$

* The simplistic model assumes that D_2 should not carry any current and hence there cannot be any voltage to current conversion.

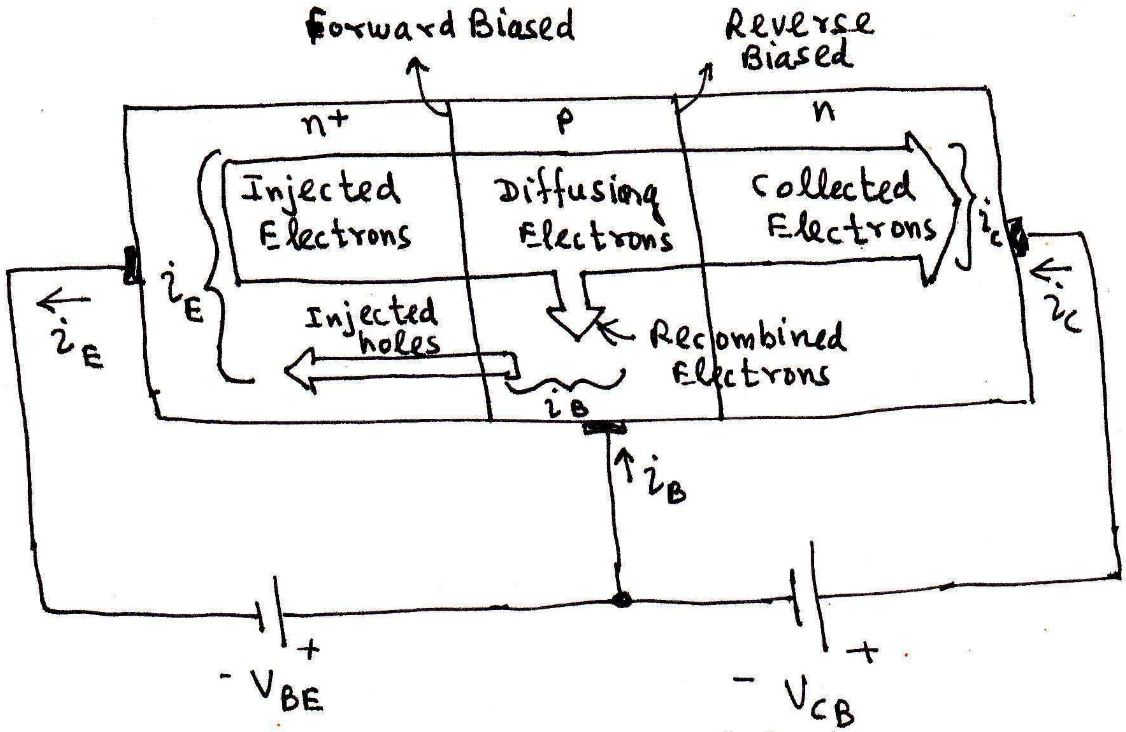
MOTION OF CARRIERS IN SLOW MOTION:-



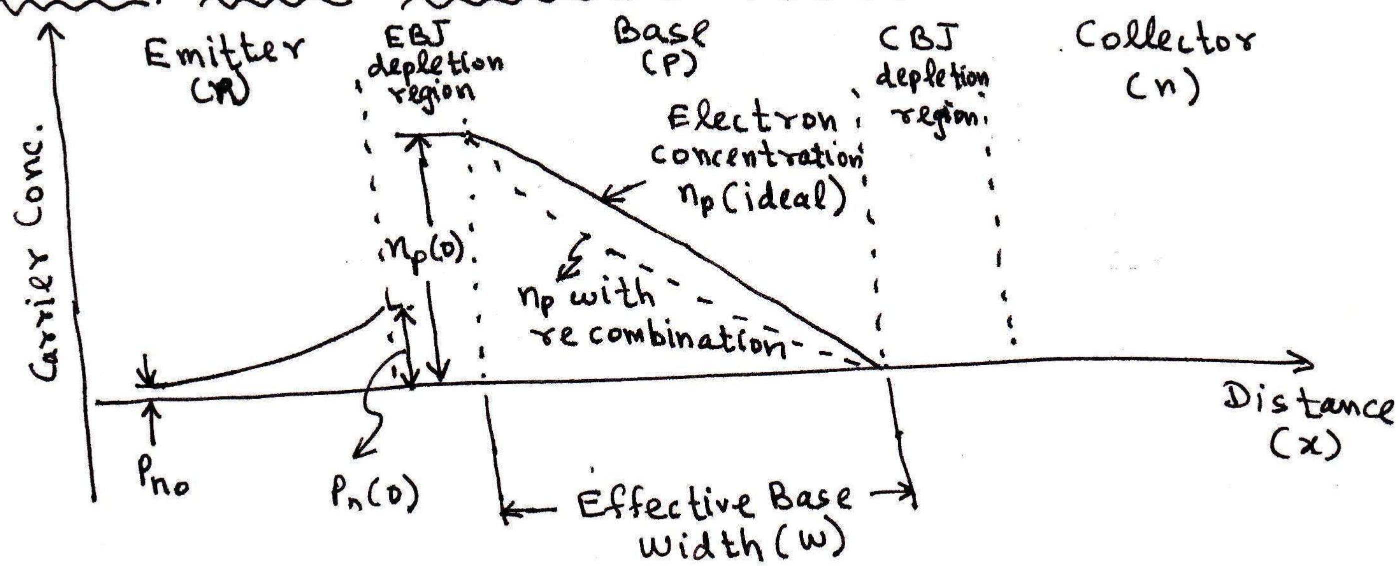


* Emitter is heavily doped.
* Base is thin.

Illustration of Current flow:-



Minority Carrier Concentration Profile:-



* Since base is very thin

$\Rightarrow$ carrier concentration will be almost a straight line.

* why is the concentration "0" at CBJ, depletion region?
  → Since any electron reaching there is swept away by the electric field in depletion region the concentration falls to "0".

* What about recombination of electrons & holes in the base region?
  → Due to recombination the profile deviates from straight line ~~and become~~ slightly. We can ignore this while deriving the current.

* In a forward biased p-n junction the concentration,

$$n_p(0) = n_{po}\, e^{V_{BE}/V_T}.$$

where, n_{po} = thermal equilibrium value of minority-carrier concentration.

V_T = thermal voltage $\approx 25\,mV$.

V_{BE} = Forward biased base emitter voltage.

* The diffusion current in base region is,

$$I_n = A_E\, q\, D_n \frac{d\, n_p(x)}{dx}$$

$$\Rightarrow I_n = A_E\, q\, D_n \left(-\frac{n_p(0)}{w}\right)$$

where, A_E = cross-sectional area of BE junction.

$q = 1.6 \times 10^{-19}\, c$

D_n = electron diffusivity in base.

w = effective base width.

* The electrons diffusing through base get collected by the collector thus giving collector current as,

$$i_c = I_n.$$

$$\Rightarrow i_c = I_s e^{V_{BE}/V_T}$$

where, I_S = saturation current = $A_E q D_n \dfrac{n_{po}}{W}$.

Now, $n_{po} = \dfrac{n_i^2}{N_A}$, where n_i = intrinsic carrier concentration and N_A = doping concentration in base.

Thus,

$$I_S = \frac{A_E q D_n n_i^2}{N_A W}.$$

* I_S i_c dependent on V_{CB}??

No.

→ So what do we have?

→ A current source between collector & emitter.

* What about the base current?

It has two components:-

① Due to holes injected from base region to emitter. This is given by,

$$i_{B1} = \frac{A_E q D_p n_i^2}{N_D L_p} e^{V_{BE}/V_T}$$

where, L_p = diffusion length (related to excess minority carrier lifetime).

D_p = hole diffusivity.

N_D = doping concentration in emitter.

② Due to holes that have to be supplied by external circuit in order to replace holes lost from the base through recombination.

$$i_{B2} = \frac{Q_n}{\tau_b}$$

where, τ_b = average time for minority electron to recombine with majority hole in the base.

Q_n = minority carrier charge stored in the base.

$$\Rightarrow Q_n = A_E q \times \frac{1}{2} n_p(0) W \quad \ldots \quad [\text{Area of triangle.}]$$

$$\Rightarrow Q_n = \frac{A_E q W n_i^2}{2 N_A} e^{V_{BE}/V_T} \quad \ldots \quad \because n_p(0) = n_{p0} e^{V_{BE}/V_T}$$

$$\text{or, } n_p(0) = \frac{n_i^2}{N_A} e^{V_{BE}/V_T}$$

Thus,

$$i_{B2} = \frac{1}{2} \frac{A_E q W n_i^2}{\tau_b N_A} e^{V_{BE}/V_T}$$

Hence, total base current is,

$$i_B = i_{B1} + i_{B2}$$

$$\Rightarrow i_B = I_S \left[\frac{D_P}{D_N} \frac{N_A}{N_D} \frac{W}{L_p} + \frac{1}{2} \frac{W^2}{D_n \tau_b} \right] e^{V_{BE}/V_T}$$

We know,

$$i_c = I_s e^{V_{BE}/V_T}.$$

Thus,

$$i_B = \frac{i_c}{\beta}$$

$$\text{where, } \beta = \frac{1}{\left(\frac{D_P}{D_N} \frac{N_A}{N_D} \frac{W}{L_p} + \frac{1}{2} \frac{W^2}{D_n \tau_b} \right)}$$

* β is typically around 50 to 200.
* β is called common-emitter current gain.
  → What is β in a MOS??
* For high β :-
  → Base should be thin (W)
  → Emitter should be heavily doped than base i.e. $N_D \gg N_A$.

Emitter Current :- Since current entering a transistor must leave it, we have,

$$i_E = i_C + i_B$$

$$\Rightarrow i_E = (\beta + 1)\, i_B .$$

$$\Rightarrow i_E = \frac{\beta+1}{\beta}\, i_C .$$

Sometimes i_C is expressed in terms of i_E leading to the following,

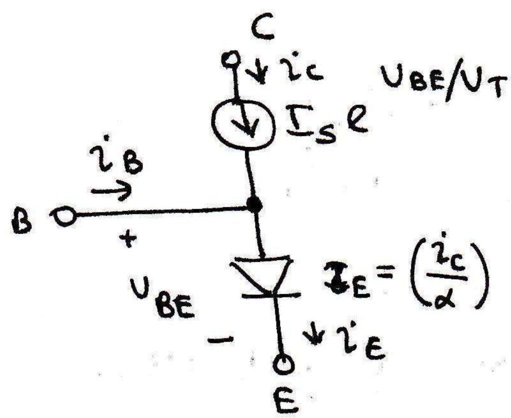
$$i_C = \frac{\beta}{\beta+1}\, i_E$$

or, $i_C = \alpha\, i_E$ ... where, $\alpha = \dfrac{\beta}{\beta+1}$.

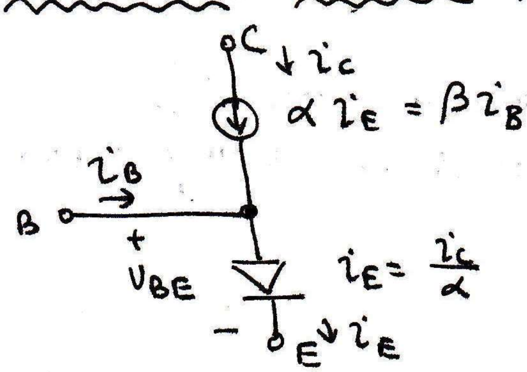
* α = Common Base Current Gain.

LARGE SIGNAL EQUIVALENT CIRCUIT MODEL

(i) Voltage-Controlled- Current Source :-



(ii) Current-Controlled Current Source :-



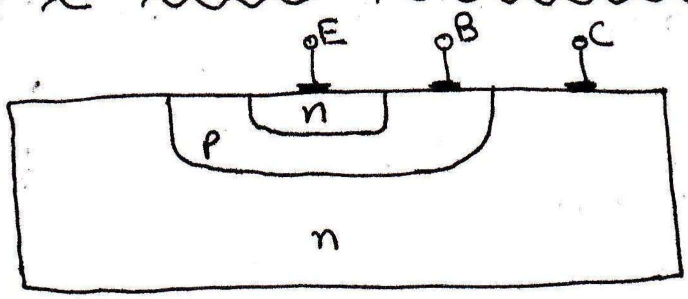
BJT Modes Of Operation :-

Mode	EBJ	CBJ
① Cutoff	Reverse	Reverse
② Active	Forward	Reverse
③ Reverse Active	Reverse	Forward
④ Saturation	Forward	Forward.

* The "α" and "β" derived earlier is for active mode also sometimes called "forward active" mode to distinguish it from "reverse active" mode.
* "α_F" & "β_F" are for "forward active" mode.
* "α_R" & "β_R" are for "reverse active" mode.

Note :- Since BJT is rarely used in reverse active mode, whenever we use "α" & "β" we mean "α_F" and "β_F".

Structure Of Actual Transistor :-

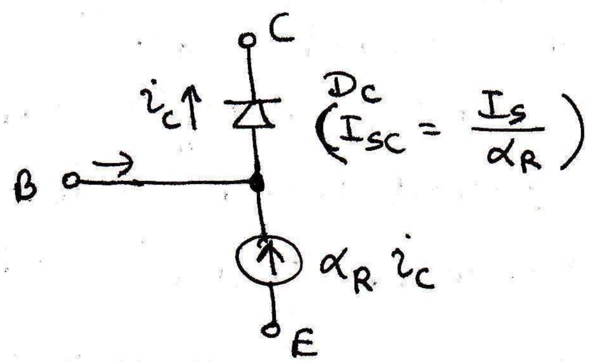


* CBJ has a much larger area than EBJ.
* If the roles of collector and emitter are reversed then we say the transistor is in "reverse active" mode.
* So in reverse active mode we should have "α_R" and "β_R".

* Typically "α_R" is in the range 0.01 to 0.5 and "β_R" is in the range 0.01 to 1.

* "α_R" and "β_R" are few orders of magnitude lower than "α_F" and "β_F".

LARGE SIGNAL MODEL FOR NPN TRANSISTOR IN REVERSE ACTIVE MODE :-

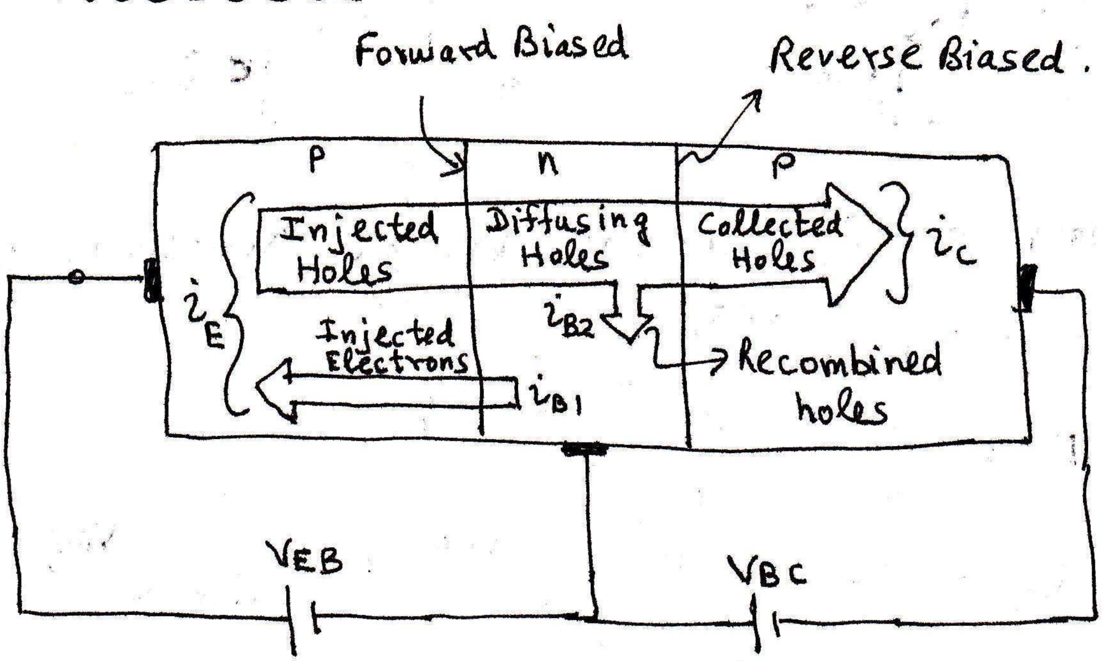


NOTE :-

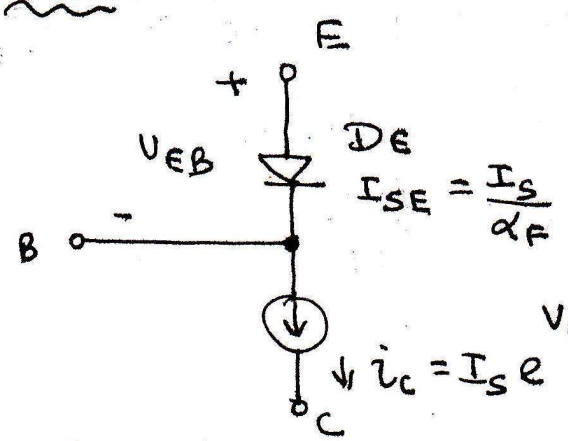
SATURATION IN BJT $\equiv$ TRIODE IN MOS

ACTIVE IN BJT $\equiv$ SATURATION IN MOS

PNP TRANSISTOR :-



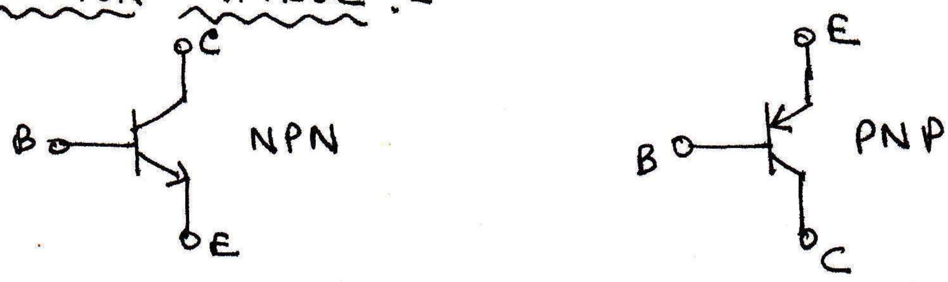
Large Signal Model for PNP transistor in Forward Active Mode :-



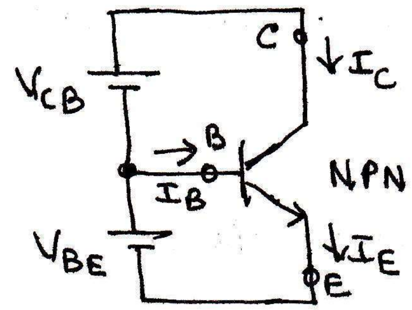
$I_{SE} = \frac{I_S}{\alpha_F}$.

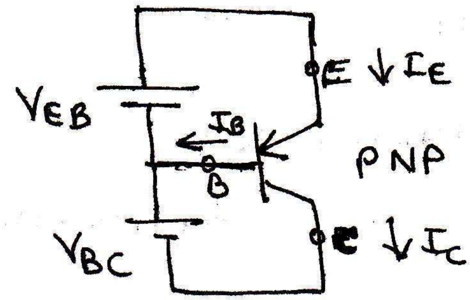
$i_C = I_S e^{V_{EB}/V_T}$

TRANSISTOR SYMBOL :-



Voltage Polarities And Current Flow in Transistors biased in active mode:-





Summary Of BJT Current Voltage Relationship In Active Mode:-

① $I_C = I_S e^{V_{BE}/V_T}$

② $I_B = \frac{I_C}{\beta} = \left(\frac{I_S}{\beta}\right) e^{V_{BE}/V_T}$

③ $I_E = \frac{I_C}{\alpha} = \left(\frac{I_S}{\alpha}\right) e^{V_{BE}/V_T} = I_{SE}\, e^{V_{BE}/V_T}$.

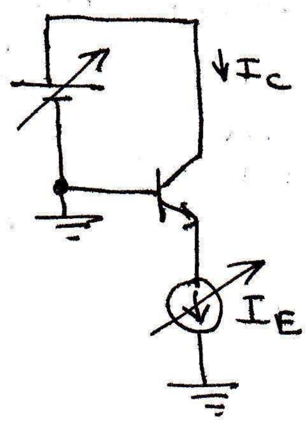
$\boxed{\text{For PNP, replace } V_{BE} \text{ with } V_{EB}}$

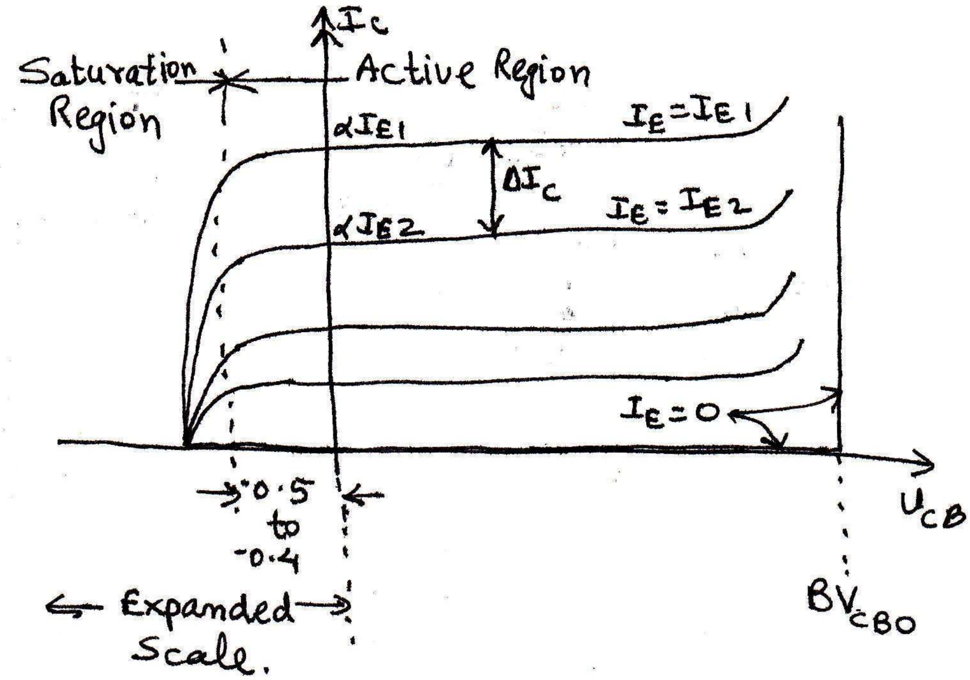
④ $I_C = \alpha I_E$, $I_B = (1-\alpha) I_E = \frac{I_E}{\beta+1}$

⑤ $I_C = \beta I_B$, $I_E = (\beta+1) I_B$

⑥ $\beta = \frac{\alpha}{1-\alpha}$, $\alpha = \frac{\beta}{\beta+1}$.

COMMON BASE TRANSISTOR CHARACTERISTICS :-



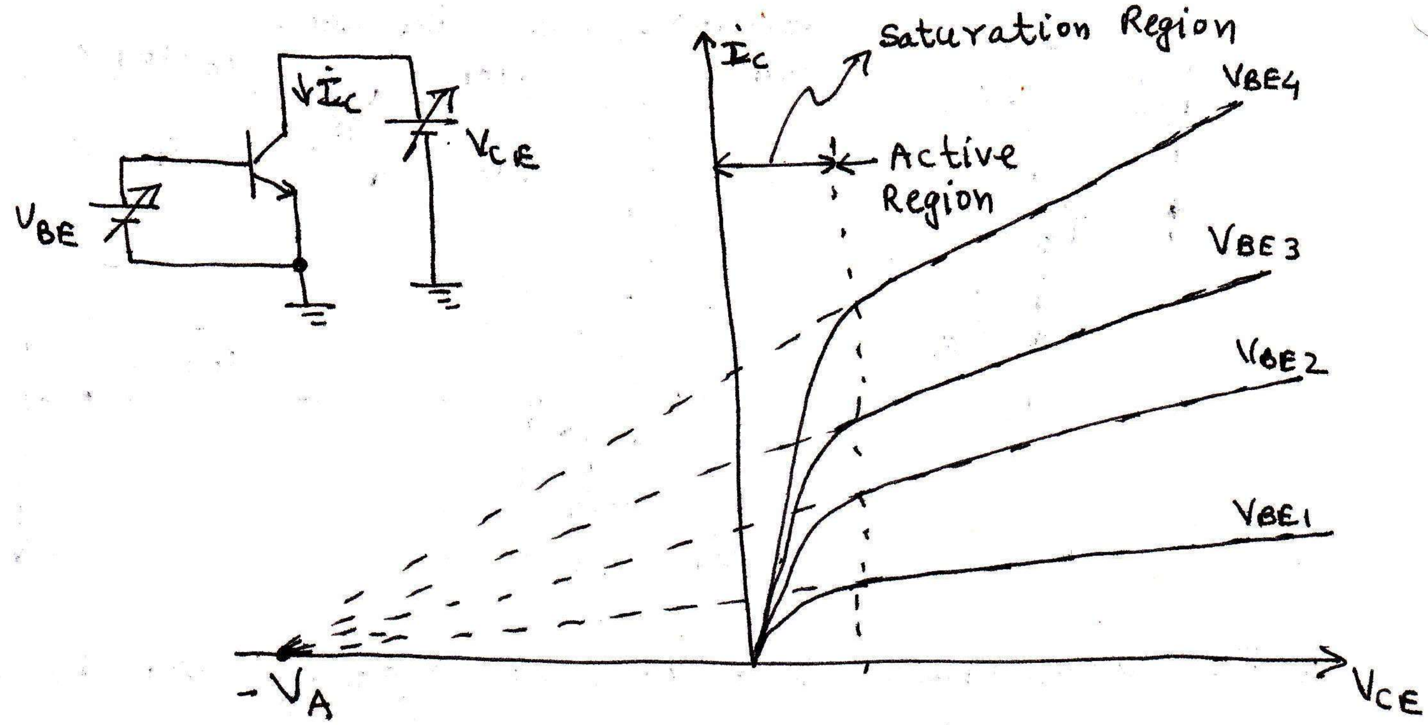


* The curves intersect Y-axis at αI_E, where I_E is constant emitter current, and α is "large signal" α.

* An "incremental" or "small signal" α is given by,

$$\alpha_{\text{small-signal}} = \frac{\Delta I_C}{\Delta I_E}.$$

DEPENDENCE OF I_C ON COLLECTOR VOLTAGE – EARLY EFFECT :-



For a particular V_{BE} we have,

$$I_C = A_E q D_n \frac{n_{po}}{W} e^{V_{BE}/V_T}$$

$$\text{or, } I_C = \underbrace{A_E q \frac{D_n n_i^2}{N_A W}}_{I_S} e^{V_{BE}/V_T}$$

* We see, $I_S \propto \frac{1}{W}$ ⇒ if W reduces I_S increases.
* what defines W ? i.e. effective base width?
* Increasing V_{CE} for particular V_{BE}, is going to increase CBJ depletion width ⇒ W reduces.
* If W reduces I_S increases ⇒ I_C increases.
* Discovered by, J.M. Early ⇒ found extrapolated characteristics all meet at one point called EARLY VOLTAGE.

* The linear dependence of I_c on V_{CE} can be accounted by assuming I_S doesn't change but adding additional factor $\left(1+\frac{V_{CE}}{V_A}\right)$ to I_c as shown below:-

$$I_C = I_S\, e^{V_{BE}/V_T}\left(1+\frac{V_{CE}}{V_A}\right)$$

* Since, I_c changes with V_{CE} there has to be a resistance associated with it and it is called the output resistance "r_o".

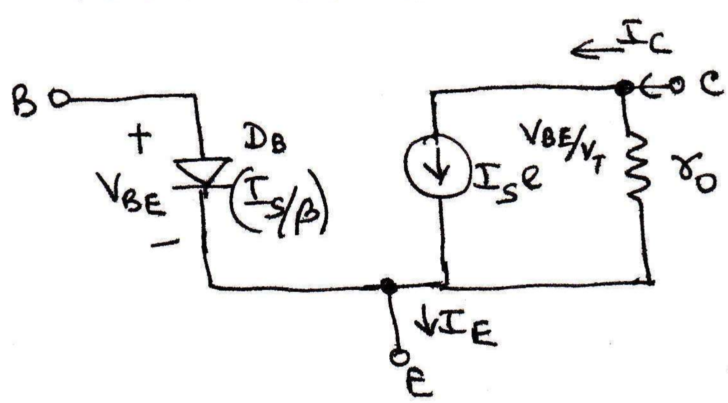
$$r_o = \left[\left(\frac{\partial I_c}{\partial V_{CE}}\right)_{V_{BE}=\text{constant}}\right]^{-1}$$

$$\Rightarrow\ r_o = \frac{V_A}{I_c}$$

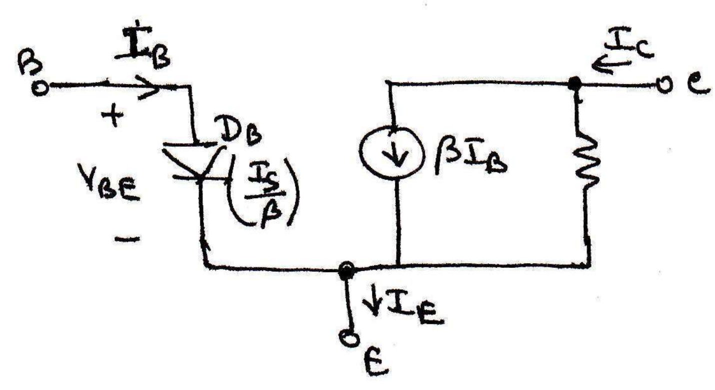
~~* Typically $V_{CE} << V_A$, thus,~~

where, $I_C = I_S\, e^{V_{BE}/V_T}$ is the current with "Early Effect" neglected.

* LARGE SIGNAL MODEL WITH EARLY EFFECT:-

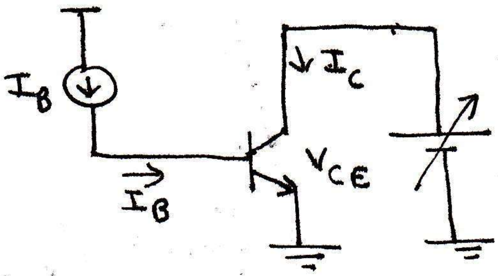


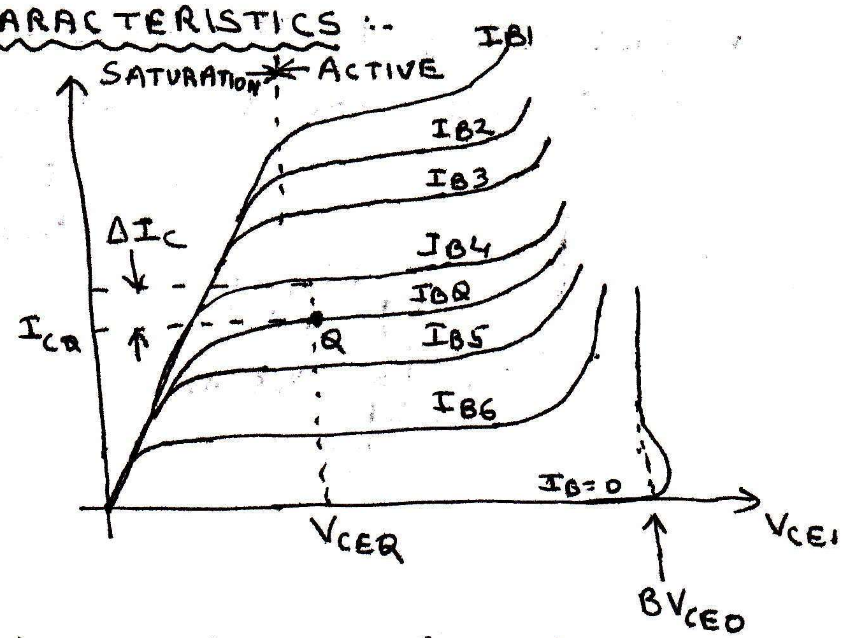
VCCS Model



CCCS Model

COMMON EMITTER CHARACTERISTICS :-





* Common emitter current gain is simply called β (to be more precise β_F).

* At the operating point,

$$\beta_{dc} \equiv \frac{I_{CQ}}{I_{BQ}}$$

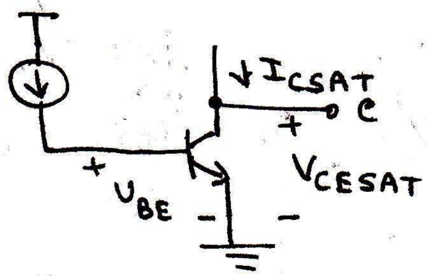
This is called large signal or dc β.

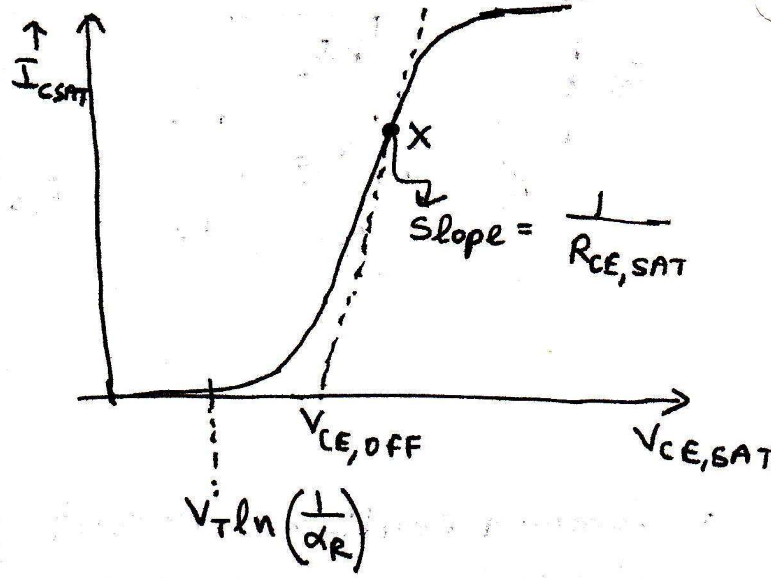
* Incremental or ac β is given by,

$$\beta_{ac} = \left.\frac{\Delta I_C}{\Delta I_B}\right|_{V_{CE} = \text{constant}}.$$

* β_{ac} and β_{dc} differ in magnitude by approx. 10 to 20%.
* For this course, β_{ac} and β_{dc} will not be differentiated i.e. we won't make a distinction between the two.

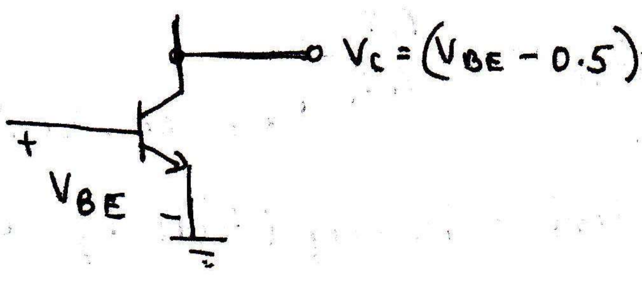
* Just like a MOSFET in triode region a saturated BJT acts like a resistor.





$$R_{CE,SAT} = \left.\frac{\partial V_{CE}}{\partial I_C}\right|_{\substack{I_B = \text{some value} \\ I_C = I_{CSAT}}}$$

* Note that Base-Collector junction get forward biased and carries substantial current when base is greater than collector by 0.5 Volts atleast.



$\Rightarrow V_{CE,SAT} \approx 0.2V$

SMALL SIGNAL OPERATION AND MODELS :-

Convention :-

$$v_{BE} = \underset{DC}{V_{BE}} + \underset{AC}{v_{be}}$$

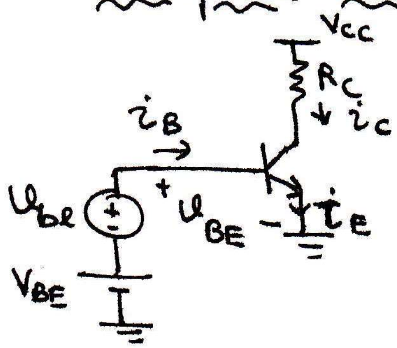
$$v_{CE} = V_{CE} + v_{ce}$$

$$i_C = I_C + i_c$$

$$i_B = I_B + i_b$$

$$i_E = I_E + i_e$$

Conceptual circuit to arrive at small signal model :-



At DC (i.e. no ac signal applied).

$$I_C = I_S e^{V_{BE}/V_T}$$

$$I_E = I_C/\alpha$$

$$I_B = I_C/\beta$$

$$V_C = V_{CE} = V_{CC} - I_C R_C$$

With ac signal :-

$$v_{BE} = V_{BE} + v_{be}$$

$$\Rightarrow i_C = I_C + i_c$$

$$\Rightarrow i_C = I_S e^{(V_{BE} + v_{be})/V_T}$$

$$\Rightarrow i_C = I_S e^{V_{BE}/V_T} e^{v_{be}/V_T}$$

$$\Rightarrow i_C = I_C e^{v_{be}/V_T}$$

$$\Rightarrow i_C = I_C \left(1 + \frac{v_{be}}{V_T}\right) \dots$$ [By Taylor series expansion with $\frac{v_{be}}{V_T} << 1$]

Thus, $$i_C = I_C + \frac{I_C}{V_T} v_{be}$$

$\Rightarrow$ small signal, $i_c = \frac{I_C}{V_T} v_{be}$

$\Rightarrow$ Transconductance, $g_m = \frac{I_C}{V_T}$.

* Can you prove that, $g_m = \left.\frac{\partial i_C}{\partial v_{BE}}\right|_{i_C = I_C}$?

Now, $$i_C = I_S e^{v_{BE}/V_T}$$

$$\Rightarrow \frac{\partial i_C}{\partial v_{BE}} = \frac{I_S}{V_T} e^{v_{BE}/V_T}$$

$$\Rightarrow \frac{\partial i_C}{\partial v_{BE}} = \frac{I_C}{V_T}.$$

* Unlike MOSFET where there is no gate current at DC, we have a base current in BJT at DC.

* Now,

$$i_B = I_B + i_b$$

$$\Rightarrow i_B = \frac{I_C}{\beta} + \frac{I_C}{\beta V_T} v_{be}$$

Thus, $$i_b = \frac{g_m}{\beta} v_{be}$$

$$\Rightarrow \frac{v_{be}}{i_b} = \frac{\beta}{g_m} = r_\pi$$ = small signal input resistance between base and emitter.

Thus, small signal model of BJT is as follows:-